TP 5417E

TESTS

OF THE

NEO-KEN SWITCHED RELUCTANCE MOTOR

Prepared for
Transportation
Development Centre

March 1984

By

DSMA ATCON LTD.
Project No. 1360

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by

W.K. Lacey, P.Eng.
DSMA ATCON LTD.
Edmonton, Alberta

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The contents of this report reflect the views of the contractor and not necessarily the official view or policies of the Transportation Development Centre.

PROJECT TEAM

The motor test bed, power source and dynamometer were supplied by B & B Electric Motor Rewinding Ltd., of Edmonton, Alberta.

The motor was wired, instrumented, and operated by the inventor, Mr. R. Kenwell of Neo-Ken Electrical Industries Limited, of Edmonton, Alberta.

The tests were specified and witnessed by Mr. W.K. Lacey, P.Eng. of DSMA ATCON LTD., Edmonton, Alberta.

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17 Abstract

The Neo-Ken D.C. brushless, reluctance-type motor was tested for torque and efficiency throughout its range of rated output and speed to determine its suitability in electric vehicle and traction applications.

Various pole configurations including series, parallel and partial series-parallel were used in the tests. Phase advance was used to optimize torque.

Efficiencies up to 70% were attained, even with the inadequate control system available. An extrapolation of the results suggests that very high efficiencies would be obtained with an improved control system.

The tests suggest, even at this stage of its development, that the motor has considerable commercial potential.

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17 Resume

Le moteur Neo-Ken, C.C. de type réluctance sans balai, a été soumis à des essais de couple et d'efficacité à travers sa gamme de puissance et de vitesse afin d'établir son aptitude à être utilisé dans des véhicules électriques et comme moteur de traction dans d'autres applications.

Plusieurs configurations de poles, incluant en série, en parallèle et en série-parallèle partielle ont été utilisées au cours des essais. L'avancement de phase a été utilisé afin d'optimiser le couple.

Une efficacité de 70% a été atteinte malgré les imperfections du système de contrôle utilisé. Une extrapolation des résultats suggère que de très hautes efficacités seraient atteintes avec un système de contrôle amélioré.

Les essais suggèrent que, même à ce stage de son développement, le moteur a un potentiel commercial considérable.

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The presence of the motor inventor, Mr. R. Kenwell, throughout the tests was absolutely essential. His intimate knowledge of the motor and control circuitry, and operating experience with the system, was necessary to implement system reconfigurations, and maintain the control system.

SUMMARY

This report presents the results of tests done on a switched reluctance electric motor, conceived and built by Mr. R. Kenwell of Neo-Ken Electrical Industries Limited.

Electrical and torque measurements for several different connection arrangements, current limits, loads, and speeds were made. Power in and out, and efficiencies were calculated from these measurements.

Run-down no-load tests were also conducted and used with an estimated calculation of rotor inertia to calculate friction and windage losses.

Test Results

The motor was first run in the 'high-speed' parallel pole-pair connection mode, with the current limit set at a high, but considered safe, level. These were maximum torque tests, but the motor could only be run from about 1150 to 800 rpm before transistors started exploding.

Torque and efficiency were both increasing as speed was reduced until the runs were terminated. Typical results at about 850 rpm were 135 NM torque, 68% efficiency, and 12 kW mechanical output.

A second series of similar tests, but with a reduced current limit, allowed a full speed range from 1200 to 165 rpm to be achieved, but with efficiencies of approximately 48% until the region below 200 rpm was entered where the efficiencies dropped to about 22%. The mechanical output ranged from about 5.8 KW at the high speed end to nearly zero at the low speed end. Torque increased from 37 to 50 NM from low to high speed.

A third series of tests with the motor connected in the 'low-speed' series connected pole-pair mode, and with low current limits, gave a nearly constant torque of 54 NM from 300 to 900 rpm. Torque increased to 66 NM at 200 rpm and decreased to 42 rpm at speeds above 900 rpm. Efficiencies ranged from 11 to 55% and mechanical output from 1.5 to 5 KW from low to high speed.

Conclusions

Limitations of the control system never allowed the motor to be tested to its full potential. At no time was the motor able to be run to a point where it started to get hot.

This motor has many attractive and promising possibilities which could be demonstrated with a proper control system. Ultimately, with a good electrical, mechanical, and thermal design optimization, it should be possible to operate this type of motor with virtually any speed/torque characteristic with good efficiency.

RÉSUMÉ

Ce rapport rend compte du résultat des essais d'un moteur électrique à réluctance variable construit et réalisé par M.R. Kenwell de la firme Neo-Ken Electrical Industries Limited.

Des mesures électriques et de couple ont été faites sous divers modes de connexion des pôles et dans des conditions variables de courants admissibles, de charges et de vitesses de rotation. Les mesures obtenues ont servi à calculer les rendements et à déterminer les puissances à l'entrée et à la sortie.

Enfin, des essais de marche sur l'erre à vide ont été faits dans le but de déterminer les pertes dues au frottement mécanique et celles dues au frottement dans l'air, sachant approximativement la valeur de l'inertie du rotor.

Resultats

La première serie d'essais a été faite à plein régime, paires de pôles connectées en parallèle et courants admissibles réglés à un niveau élevé mais néanmoins sécuritaire. On voulait connaître les couples maximums fournis mais pour empêcher la défaillance des semi-conducteurs, la plage des vitesses de rotation a dû être maintenue entre 1150 et 800 tr/min.

Le couple et le rendement augmentaient à mesure que la vitesse diminuait. Pour un régime de 850 tr/min environ, un couple de l'ordre de 135 N.m, un rendement de 68 p. cent et une puissance de 12 kW à la sortie ont pu être obtenus.

La deuxième série d'essais, effectuée à des courants admissibles moins élevés, a autorisé une gamme complète de vitesses, soit entre 1200 et 165 ti/min. Les rendements correspondants sont tombés autour de 48 p. cent et ils n'ont été que de 22 p. cent lorsque les vitesses ont chuté sous 200 tr/min. La gamme des puissances de sortie s'est située entre 5,8 kW à régime élevé et 0 ou presque, à faible régime. Les couples correspondants ont fluctué entre 50 et 37 N.m, respectivement.

Enfin, pour la troisième série d'essais, une valeur de couple constante de 54 N.m entre 300 et 900 tr/min a pu être obtenue, les paires de poles étant connectées en série et les courants admissibles encoure plus faibles. Les couples fournis ont atteint 66 N.m à 200 tr/min et sont tombes à 42 N.m autour de 900 tr/min. Les rendements ont fluctué entre 11 et 55 p. cent et les puissances de sortie entre 1,5 et 5 kW, selon que le régime était faible ou fort.

Conclusions

Le système de commande du moteur n'a pas permis de pousser le moteur à fond, et encore moins de lui faire atteindre le point d'échauffement.

Doté d'une commande appropriée, ce moteur est intéressant et prometteur. Sous réserve d'une étude optimisant ses caractéristiques électriques, mécaniques et thermiques, il serait possible de le faire fonctionner pratiquement à n'importe quelle courbe vitesse-couple tout en obtenant un rendement intéressant.

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1. INTRODUCTION

This report presents the results of performance tests of a 'bread-board' model of a 4-phase, 12 pole, switched reluctance brushless D.C. motor, hereinafter referred to as the NEO-KEN motor.

The motor is a unique configuration of a reluctance motor in which the field poles are mounted on a stator inside the rotor. The rotor is made up of laminated iron bars configured in a squirrel cage fashion co-axially located outside the stator.

Torque is transmitted to the shaft through a differential in the centre of the motor which has the rotor bars connected to the differential casing at their mid-points. The motor is axially symmetrical on either side of the differential, with two phases on each side.

The field poles in each phase are physically offset by 15 mechanical, or 90 electrical, degrees from the next phase row of poles. Each pole pair occupies 15 mechanical degrees followed by a 15 mechanical degree space before the next pole/pair. Each pole/pair is made up of a laminated "U" yoke with a coil winding on each leg. The yoke opening is radially outward and the yokes are aligned axially so that the flux path through the rotor bars is axial.

The rotating field is generated by sequentially switching each phase, and the rotor bars are dragged along by the reluctance forces generated by the rotating field.

2. OBJECTIVE AND SCOPE OF TESTS

The objective of these tests was to measure the performance of the NEO-KEN motor at various loads, speeds, and field connection configurations.

It was not intended to be a reliability or life test, since this is only a 'breadboard' prototype motor.

No assessment of the power to weight or volume ratio was made, again because it is only a 'breadboard' model intended for proof of principle. A more thorough electrical and mechanical analysis will be required to evaluate such parameters.

No temperature measurements were made on any part of the motor during the tests.

3. TEST SET-UP

The tests were conducted at B & B Motor Rewinding Co. in Edmonton who provided the dynamometer system, power supply and mounted the motor.

The dynamometer was an Inductor Inc., Model CD-1222 Caliper Dynamometer rated at 100 HP short term at 1800-3600 rpm. The maximum torque capacity of 300 lb.ft. is specified from 0 - 1800 rpm.

The V_1 power source was two sets of fork-lift batteries connected in series. These were charged overnight by a D.C. power supply provided by B & B Electric.

The V_2 power sink was two sets of common lead-acid batteries, which were discharged through a large air cooled resistor when not connected.

Although the dynamometer had a built-in tachometer, a digital frequency counter attached to the commutator circuit was used to read speed. This gave better resolution than the dynamometer tach and also located the reading in the same vicinity as all the other meters.

Currents and voltages were read with inexpensive D'Arsonval type meters, connected across calibrated 0 - 400 amp 50 mv shunts for the current readings.

A schematic diagram of the test set-up is shown in Figure 1.

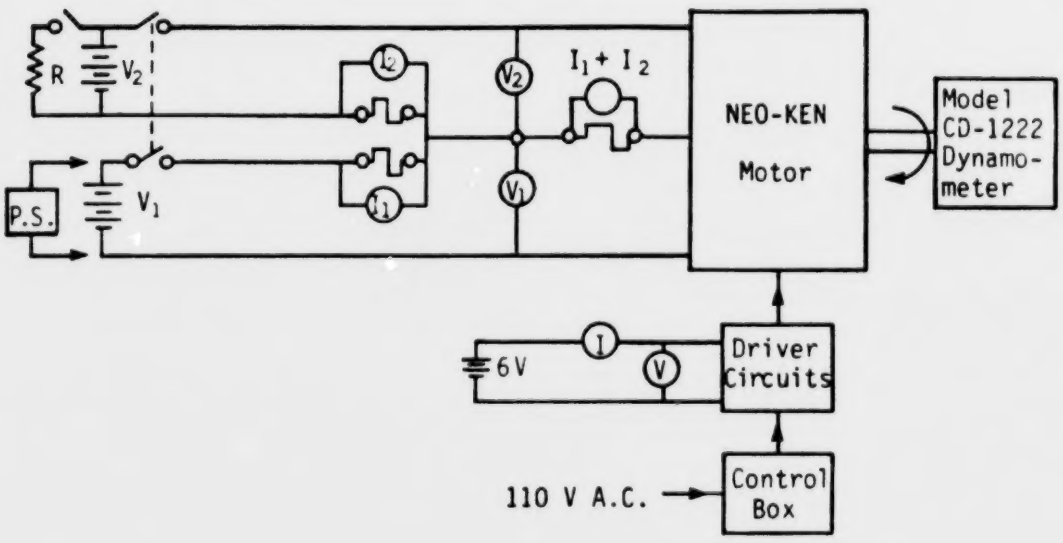

Figure 1 Neo-Ken Motor Test Set-up

4. TEST PROCEDURES AND RESULTS

4.1 'High Speed' (or Parallel) Configuration

This configuration consists of each power transistor driving two sets of pole-pair coils connected in parallel. The current limit was set at as high a level as deemed practical to protect the transistors.

The motor was run up to approximately 1000 rpm and loaded to maximum torque. This required manual adjustment of the phase advance. Several readings were taken down to approximately 800 rpm, with output torque maximized by phase adjustment.

A zero load run was also done to determine total system losses. The power transistor driver electronics are not included in these readings, but the driver transistors are.

The nominal V_1 voltage was 90 volts and the nominal V_2 voltage was 200 volts.

A short run (No. 9, 10, 11, 12) was also done with V_1 reduced in half (nominally 45 volts).

The test results are listed in Table 1 and the electrical power in and mechanical power out are plotted against speed in Figure 2.

The torque and efficiency vs speed are plotted in Figure 3.

4.2 'High Speed' Configuration - Lowered Current Limits (Table 2 and Figures 4 and 5)

These tests were run with the same configuration as described in Section 4.1, but with reduced current limits. The reasons for this are discussed in Section 5.

The field discharge voltage (V_2) was nominally the same as the driving voltage (V_1), i.e. both approximately 90 V.

Runs 13 to 17 were done with only half of the motor phases powered. The powered phases A and B are mechanically and electrically in phase opposition (i.e. 180^0).

It was attempted to keep the torque more or less constant and vary the speed by controlling the phase advance and the transistor conduction time.

Runs 13 to 21 had full conduction angle (i.e. 180^0) and variable advance.

Runs 22 to 30 varied both the advance and the conduction angle (time).

Run No.	Speed (RPM)	Torque (N.M.)	V_1 (Volts)	I_1 (Amps)	V_2 (Volts)	I_2 (Amps)	Elec. Pwr. (kW) P_{in}	P_{out}	P_{net}	Mech.Pwr. (kW)	Eff. (%)	Remarks
1	965	88.1	85	256	218	-	21.8	-	-	8.9	-	
2	999.8	0	90	80	206	20	7.2	4.1	3.1	0	0(no load)	
3	1,166.7	74.6	84	304	220	46	25.5	10.1	15.4	9.1	59	
4	916.7	128.8	81	368	220	50	29.8	11.0	18.8	12.4	66	B
5	863.7	128.8	80	360	221	50	28.8	11.1	17.7	11.7	66	
6	859.7	135.6	80	364	221	50	29.1	11.1	18.0	12.2	68	
7	852.3	135.6	79	364	221	50	28.8	11.1	17.7	12.1	68	
8	824.6	128.8	80	344	222	52	27.5	11.5	16.0	11.1	70	
9	966.8	0	46	100	199	12	4.6	2.3	2.3	0	0(no load)	V_1 reduced to 45 V
10	972.7	0	46	100	199	12	4.6	2.3	2.3	0	0(no load)	
11	995.6	12.2	44.5	176	203	16	7.8	3.2	4.6	1.3	28	A
12	982.5	12.2	44	172	203	16	7.6	3.3	4.3	1.3	29	

Table 1 Test Results - Maximum Torque, Pole Pairs Parallel Connected
(Test Run 09 March, 1984)

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Run No.	Speed (RPM)	Torque (N.M.)	V_1 (Volts)	I_1 (Amps)	V_2 (Volts)	I_2 (Amps)	Elec. Pwr. (kW)			Mech.Pwr. (kW)	Eff. (%)	Remarks
							P_{in}	P_{out}	P_{net}			
13	1206.5	0	97.6	60	87.6	34	5.8	2.98	2.8	0	0 no load	Phases A&B only
14	1215	0	97.2	60	87.7	33	5.8	2.9	2.9	0	0 no load	
15	1221.8	0	97.2	60	87.8	33	5.8	2.9	2.9	0	0 no load	
16	1040	36.6	91.5	188	100.7	70	17.2	7.0	10.2	3.99	39	
17	1053	36.6	91.9	180	100.6	68	16.5	6.8	9.7	4.04	42	
18	1157	46.1	87.5	272	110	110	23.8	12.1	11.7	5.59	48	All Phases
19	1163	47.5	87.2	272	110.7	110	23.7	12.2	11.5	5.78	50	
20	1148	48.8	86.8	280	111.3	110	24.3	12.2	12.1	5.87	49	
21	820	50.8	89	220	110.2	95	19.6	10.5	9.1	4.37	48	Variable Pole Width Max. Pole Width
22	823	44.1	89.5	196	106.7	90	17.5	9.6	7.9	3.8	48	
23	707	45.4	89.8	192	107.7	87	17.2	9.4	7.8	3.4	43	
24	605.6	44.5	91.5	136	106.5	64	12.4	6.8	5.6	2.8	50	
25	476.6	40	91.9	116	110.5	58	10.7	6.4	4.3	2.0	46	
26	306.3	41.4	92.1	112	111.5	62	10.3	6.9	3.4	1.3	39	
27	295.4	34.7	92.9	92	105.5	58	8.5	6.1	2.4	1.1	45	Variable Advance
28	220	36.6	89.8	152	117.7	88	13.6	10.4	3.2	0.84	26	
29	170	36.6	89.8	152	118.8	89	13.6	10.6	3.0	0.65	22	
30	165	37.3	89.7	152	119.0	90	13.6	10.7	2.9	0.64	22	Variable Advance

Table 2 Test Results - Maximum Torque (Lower Current Limit), Pole Pairs Parallel Connected
(Test Run 17 March, 1984)

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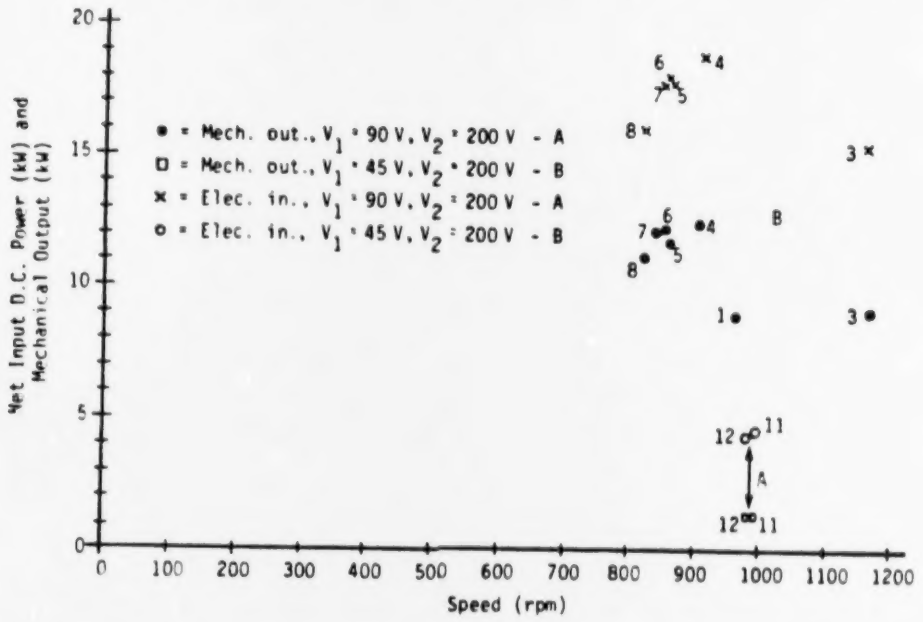

Figure 2 Net Input D.C. Power and Mechanical Output vs Speed Maximum Load. Pole Pairs Parallel Connected (Test Run 09 March, 1984)

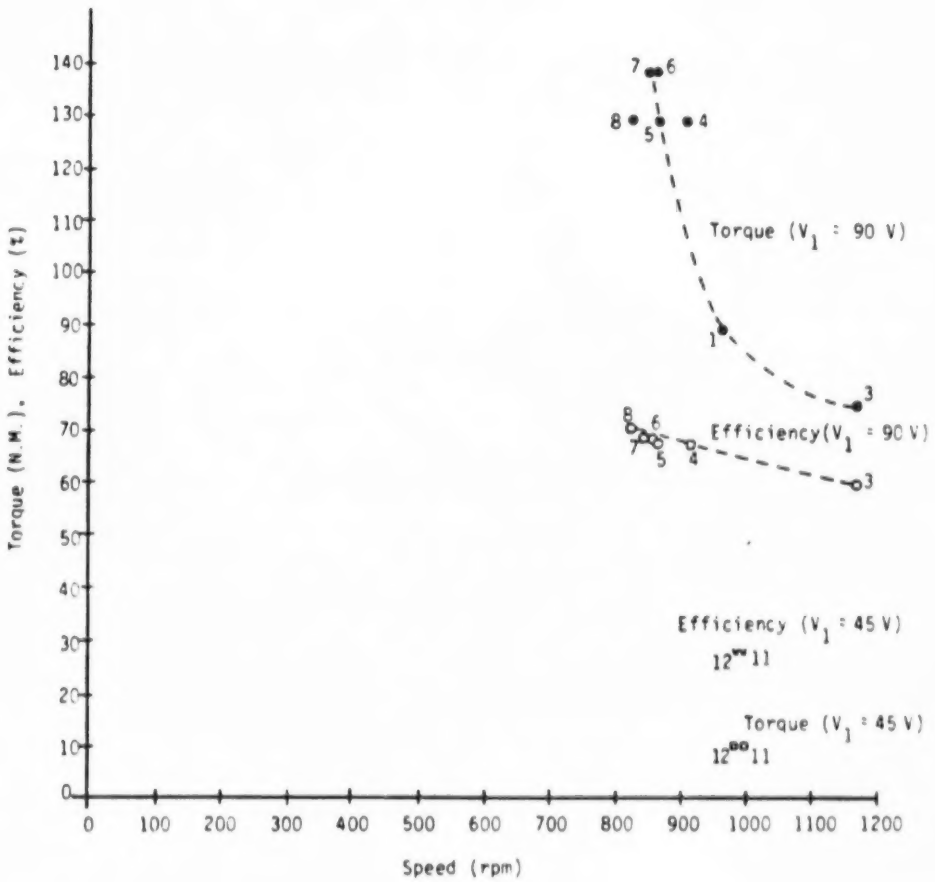

Figure 3 Torque and Efficiency vs Speed
Maximum Load. Pole Pairs Parallel Connected
(Test Run 09 March, 1984)

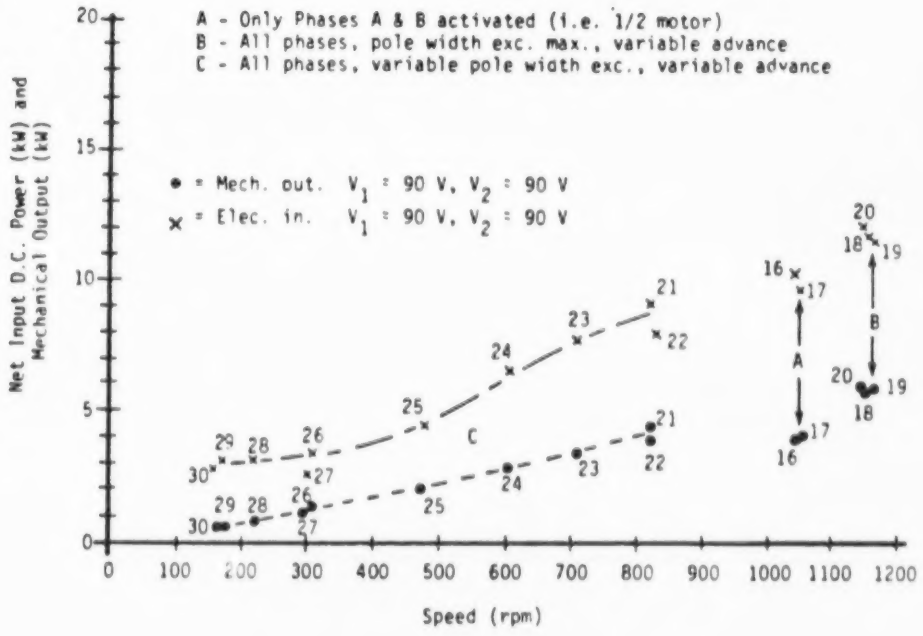

Figure 4 Net Input D.C. Power and Mechanical Output vs Speed Maximum Torque (Lower Current Limit), Parallel Connection (Test Run 17 March, 1984)

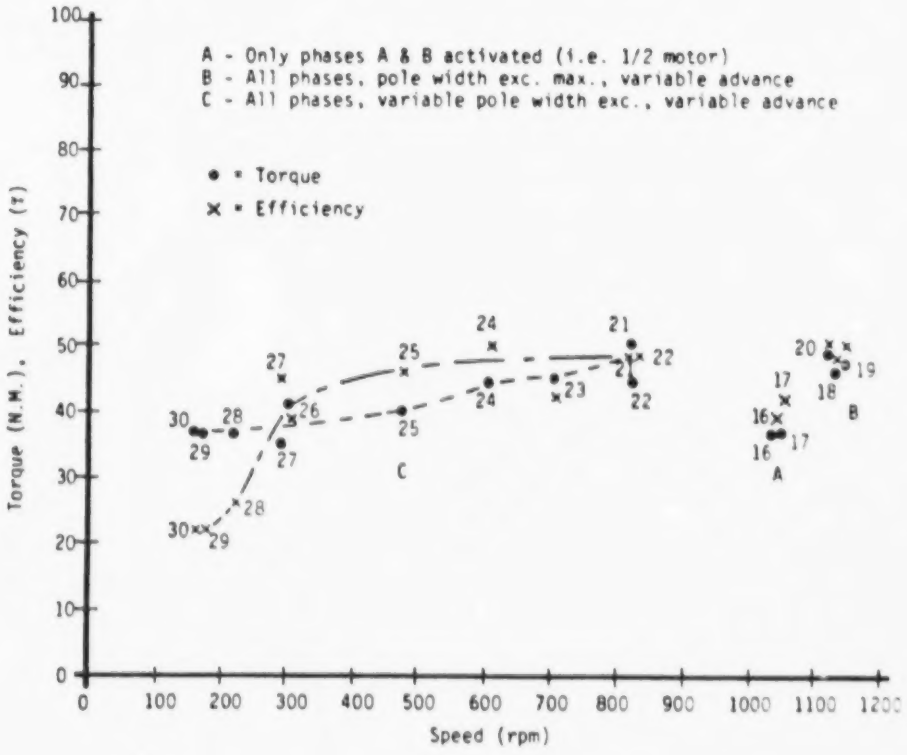

Figure 5 Torque and Efficiency vs Speed
Maximum Torque (Lower Current Limit),
Parallel Connection
(Test Run 17 March, 1984)

4.3 'Low Speed' (or Series) Configuration - Lowered Current Limits

For runs 31 to 45 the pole-pairs were connected two in series, for each power transistor (Ref. Table 3 and Figures 6 and 7).

Phase advance was varied during these tests to optimize the torque. The conduction angle was a full 180^{o}.

Runs 31 to 39 were made with all pole-pairs connected, and runs 40 to 45 had only half the pole-pairs in the circuit.

Runs 41 to 45 were no load runs to assess motor and drive system losses.

4.4 Motor Run Down Test

The motor was run up to a higher no-load speed, then all drive power was removed and the motor allowed to coast to a stop. Speed readings were taken at 5 second intervals.

The precision tachometer could not be used for this test because it was a time base operated counter and the sampling time intervals were too long for meaningful measurements. The tachometer meter on the dynamometer was used for the speed readings, and the resolution is therefore relatively coarse.

Test readings are listed in Table 4.

A first order calculated estimate of the rotor inertia was made and found to be 1.63 newton meter sec^2. The friction and windage losses for the mean speed between samples was calculated by the formula:

$$\text{Loss} = \frac{64.26}{3600} \left(\frac{n_i - n_{(i+1)}}{\Delta t} \right) \left(\frac{n_i + n_{(i+1)}}{2} \right) \text{ Watts}$$

The dynamometer brake disks were not included in the calculation, but their moment of inertia will be much less than the motor and should not significantly affect the results.

The losses are plotted in Figure 8.

Run No.	Speed (RPM)	Torque (N.M.)	V_1 (Volts)	I_1 (Amps)	V_2 (Volts)	I_2 (Amps)	$I_1 + I_2$ (Amps)	Elec. Pwr. (kW)			Mech.Pwr. (kW)	Eff. (%)	Remark
								P_{in}	P_{out}	P_{net}			
31	299	54.9	88	272	114.5	106	370	23.9	12.1	11.8	1.72	15	All coils energized
32	210	66.4	87	284	118.3	100	374	24.7	11.8	12.9	1.46	11	
33	599	53.6	89	180	104.8	67	278	16.0	7.0	9.0	3.36	37	
34	608	54.2	90	216	106.2	65	276	19.4	6.9	12.5	3.45	28	
35	727	52.9	90	200	106.1	60	252	18.0	6.4	11.6	4.03	35	
36	800	54.2	89	208	107.3	60	264	18.5	6.4	12.1	4.55	38	
37	895	54.2	90	186	108.3	57	240	16.7	6.2	10.5	5.09	48	
38	1062	42.0	91	158	109.9	54	211	14.4	5.9	8.5	4.7	55	
39	1081	42.0	91	160	111.5	54	206	14.6	6.0	8.6	4.76	55	
40	1040	54.2	83	320	110.8	82	408	26.6	9.1	15.5	5.91	38	Half of total coils energized
41	994	0	95	46	100.6	31	77	4.4	3.1	1.3	-	-	
42	745	0	96	36	99.5	24	60	3.5	2.4	1.1	-	-	
43	490	0	96	24	98.2	18	48	2.3	1.8	0.5	-	-	
44	255	0	98	18	96.5	14	34	1.8	1.4	0.4	no load test	-	
45	251	0	97.5	18	96.8	14	36	1.8	1.4	0.4	-	-	

Table 3 Test Results - Maximum Torque (Lower Current Limit)
Pole Pairs Series Connected (Runs 31 - 39)
Single Pole Pair Per Transistor (i.e. Only 24/48 coils used)(Runs 40-45)
(Test Run 18 March, 1984)

Time (Sec.)	Run 1 (RPM)	Run 2 (RPM)
0	1300	1400
5	1100	1230
10	900	1050
15	750	875
20	600	725
25	500	590
30	400	450
35	300	375
40	240	300
45	150	230
50	100	150
55	-	90

Table 4 Motor Run-Down Test
(17 March, 1984)

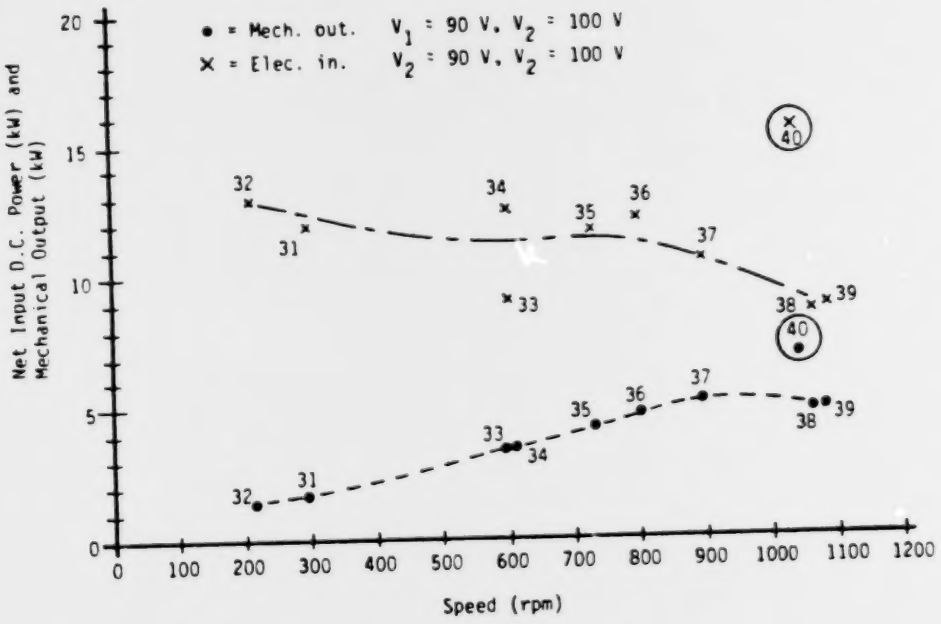

Figure 6 Net Input D.C. Power and Mechanical Output vs Speed
Pole Pairs Series Connected (Runs 31-39)
Single Pole Pair Per Transistor (i.e. only $\frac{24}{48}$ coils used)
(Run 40)
(Test Run 18 March, 1984)

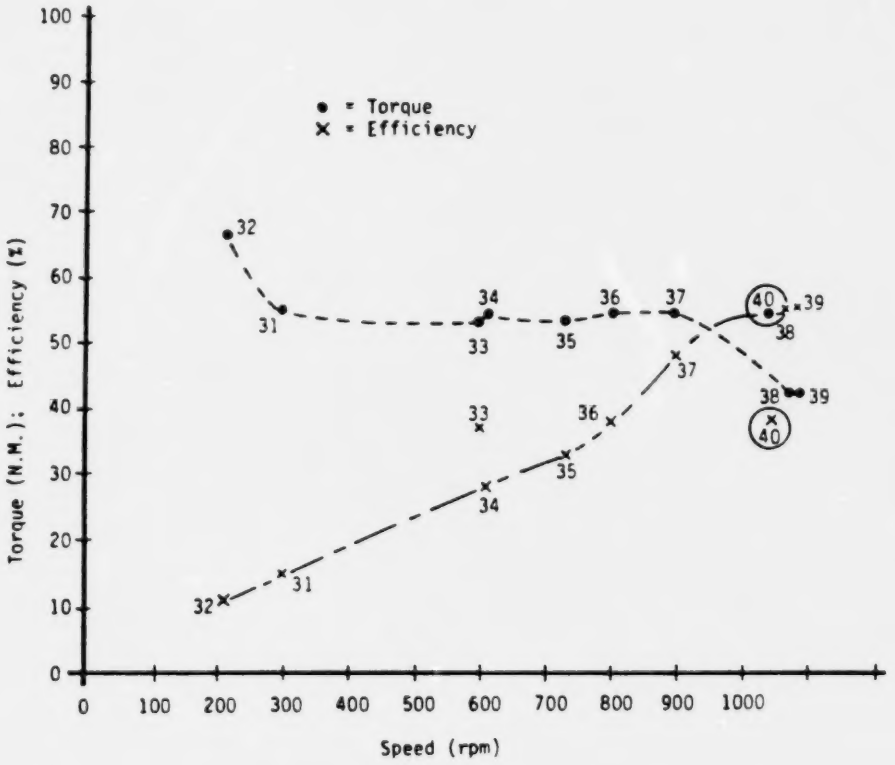

Figure 7 Torque and Efficiency vs Speed
Pole Pairs Series Connected (Runs 31-39)
Single Pole Pair Per Transistor (i.e. only $\frac{24}{48}$ coils used)(Run 40)
(Test Run 18 March, 1984)

Moment of Inertia (calculated) = 1.2 lb ft. sec^2

= 1.63 Newton Meter sec^2

$$\text{Average loss} = \frac{64.26}{3600}\left(\frac{n_1-n_2}{\Delta t}\right)\left(\frac{n_1+n_2}{2}\right) \text{ Watts} \quad \text{——— (1)}$$

Run #1 Δt = 5 sec. Run #2

t (sec)	$\frac{n_1-n_2}{\Delta t}$	$\frac{n_1+n_2}{2}$	Loss (Watts)
0	40	1200	857
5	40	1000	714
10	30	825	442
15	30	675	362
20	20	550	196
25	20	450	161
30	20	350	125
35	12	270	58
40	18	195	63
45	10	125	22
50			

t (sec)	$\frac{n_1-n_2}{\Delta t}$	$\frac{n_1+n_2}{2}$	Loss (Watts)
0	34	1315	798
5	36	1140	733
10	35	962.5	601
15	30	800	428
20	27	657.5	317
25	28	520	260
30	15	412.5	110
35	15	337.5	90
40	14	265	66
45	16	190	54
50	12	120	26
55			

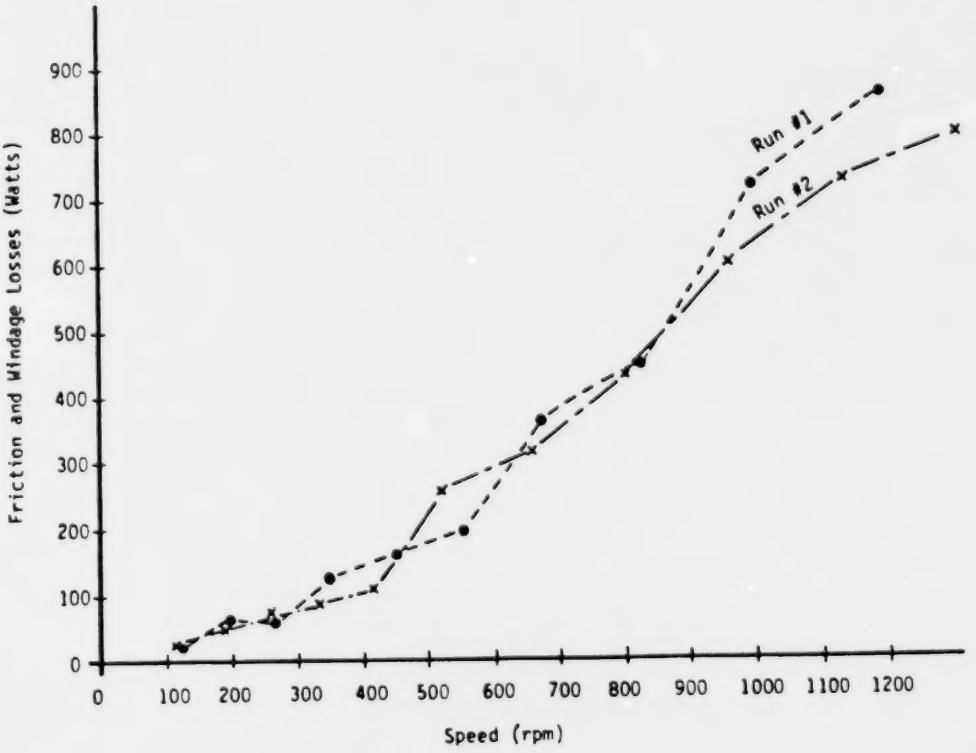

Figure 8 Friction and Windage Losses vs Speed

Note: This does not include the inertia of the dynamometer disks, and is therefore lower than the correct losses.

5. COMMENTS ON TEST RESULTS

5.1 Tests on 09 March, 1984

The initial tests conducted on 09 March, 1984 were with the current limits set at a level deemed necessary to protect the power transistors.

Runs 1 to 8 were only made down to about 800 rpm and the efficiency was improving as the speed was lowered. This is normal.

Runs 9 to 12 were made at half the previous input voltage, with 9 and 10 being no load tests which gave total system losses (less transistor drive electronics) of 2.3 kW. Runs 11 and 12 showed a significant torque decrease and the efficiency also dropped to about half the full input voltage values.

Subsequent to these tests, attempts to run at higher loadings, and hence higher currents, resulted in power transistors exploding.

There is no indication that the motor was ever operating at its full capability because the iron barely warmed up and the copper never got excessively warm.

Subsequent to these tests several attempts were made to improve the drive transistor power handling capabilities, but because of basic circuit, component, and time limitations, none of these were successful.

Mr. Kenwell then put all the control circuits back in serviceable condition and cut down the current limits to a value which would protect the transistors over all speed regimes. This unfortunately meant that the motor was never run to its full capability.

5.2 Tests on 17 March, 1984

These tests were run with the motor in the same configuration as runs 1 to 12, but with a lower current limit setting and with the field discharge voltage (V_2) approximately the same as the drive voltage (V_1). This was done to approximate a single voltage power system with regeneration, which should ultimately be a better system for any battery driven vehicle application.

The efficiencies and torques were not as high as the previous runs, as would be expected.

It is interesting to note that the one point (Runs 16 and 17) where only two phases were powered did not result in a comparable drop in efficiency although the torque did decrease significantly.

The motor was able to run over a full speed range and was also able to start with a starting load in excess of 30 Nm.

5.3 Tests on 18 March, 1984

The motor was reconfigured with the two pole-pairs per drive transistor connected in series whereas for previous tests they were connected in parallel.

This gives better low speed torque because the total limited current level flows through each coil, whereas for the parallel connection only half this current flows through each coil. This is more noticeable at low speeds also because the current limit does not operate at high speeds. At higher speeds the current cannot rise fast enough to reach the current limit due to the 4_R time constant and the applied voltage levels.

The test results for runs 31 to 39 do indeed show a rising torque at low speeds, a characteristic similar to a series D.C. motor.

Only half the coils were connected for run 40, and higher mechanical power and torque output were achieved. This may be attributed to the shorter time constant and hence faster rise time to a higher current level before switch off.

The time constant with two coils in a series is:

$$T_2 = \frac{2L}{2R_L + R_T}$$

Where: R_L = coil resistance

R_T = transistor resistance

The time constant with only one coil per transistor is shorter:

$$T_1 = \frac{L}{R_L + R_T}$$

The losses in the latter case will increase with the square of the current, which is higher due to the shorter rise time, and therefore even though the total resistance is lowered by R the net losses increase. This accounts for the decrease in efficiency.

5.4 Losses

5.4.1 Friction and Windage

It was thought that the friction and windage losses would be high for this particular rotor configuration and a run-down test generally confirmed this, but even so only about 660 watts loss can be attributed to friction and windage at 1000 rpm according to the rough calculations and measurements in section 4.4

5.4.2 I^2R

The two main sources of I^2R loss are the coil resistances and transistor and diode losses.

Since only half the transistors are on at any time and I_1 flows through them and the coils, whereas I_2 flows through the other half of the number of coils and the diodes, the I^2R losses are primarily as follows:

Parallel connection:

$$\text{Losses} = V_{Cesat} I_1 + (I_1^2 + I_2^2) \frac{R_L}{24} + (\text{Misc. transistor and diode losses})$$

Series connection:

$$\text{Losses} = V_{Cesat} I_1 + (I_1^2 + I_2^2) \frac{R_L}{6} + (\text{Misc. transistor and diode losses})$$

Unfortunately V_{Cesat} was not measured in these tests.

5.5 Iron Losses

These are estimated to be insignificant in this motor, because the iron is not operating anywhere near saturation for most of the time. This indicates that there is more iron than necessary in this motor.

An interesting and unusual aspect of this motor configuration is that there are no flux reversals in the iron, so the hysteresis losses can be expected to be very low.

5.6 Current Measurements

The meters used to measure currents are incorrect types to be used for pulsating sawtooth currents. They read average currents, not RMS, or effective currents. Hot wire meters would have been a better, although more expensive choice.

In the case of a non-current limited, high speed mode of operation, it can be readily shown that average readings produce a lower efficiency figure than is true. The case for current limiting waveforms is not so readily analyzed so it is not possible to comment on the effects.

5.7 Current Limiting

The current limiting system causes some strange effects at times, particularly when the motor is loaded to very near the stalling point.

Possibly this is related to the fixed off interval after each switch off of the power transistor by the current limit.

5.8 Phase Conduction Angle

When this control is used it is a timed interval controlled by a potentiometer which only gives a constant conduction angle for a constant speed. This is an unstable situation, since if the load increases and the motor slows, the actual conduction angle decreases and therefore reduces the drive to the motor.

This conduction angle control should somehow be related to the motor speed.

6. CONCLUSIONS

This motor concept has many attractive and promising possibilities, but these tests have not brought out the maximum potential of even this 'breadboard' model, because of the limitations of the control system.

A properly engineered control system capable of delivering currents the motor could stand and of operating on a single voltage source will undoubtedly demonstrate significant improvement in motor performance.

It is not fair to pass any comment on power-to-weight or volume ratio for this motor because it is really only a 'breadboard' model. There is more iron than necessary in the magnetic circuit, and the form factor of the coils could be improved by using much of the vacant space between the phases or reducing the length.

A thorough analysis of this motor and control methods would indicate many areas of improvement and would provide essential engineering design data.

The wide variety of control options and connection configurations of poles and phases will permit this motor concept to be tailored to virtually any motor characteristic desired, except perhaps very low inertia applications.

It is readily adaptable to computer control and can operate in a speed or position mode similar to a stepping motor.

It could eliminate the need for gearboxes in many applications, and Mr. Kenwell's inclusion of a differential drive built into the motor is an attractive configuration for traction uses.

The power control circuits need not be any more complicated than those used to control induction motors from a D.C. source. Higher power transistors and other devices are already available which will reduce the number of devices required or conversely increase the drive power.